

Forecasting Future Sea Ice Conditions in the MIZ: A Lagrangian Approach

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LONG-TERM GOALS

- 1- Determine the source regions for sea ice in the seasonally ice-covered zones (SIZs) using back trajectories calculated from satellite-derived sea ice drift, based on work by Maslanik et al. 1995, Emery et al. 1997a, Meier et al. 2000, Tschudi et al. 2010.
- 2- Assess whether the source region of sea ice melting in peripheral seas in the GCMs participating in the IPCC AR5 and regional sea ice models agree with observed source region patterns from the satellite-derived dataset.
- 3- Compare Lagrangian ice trajectories in model and satellite datasets.
- 4- Repeat this analysis for 4 critical climate horizons: a base period (1979-2000), the most recent decade when transition to a new sea ice regime occurred (2001-2010), and two projection periods in the 21st Century (mid and late 21st century).

OBJECTIVES

- 1- Reduce uncertainties in future sea ice extent prediction from climate models participating in CMIP5. These include temporal evolution and geographical distribution of sea ice cover and transport pathways.
- 2- Improve our understanding of the strengths and/or limitations of GCM predictions of future ice edge positions.
- 3- Identify limitations in the ability of GCMs to simulate source regions for sea ice being advected into marginal ice zones (MIZs) and thus provide guidance for developing more reliable forecasts of the future evolution of transports of material between remote areas of the Arctic.
- 4- Quantify GCM biases in the balance of thermodynamically formed, in situ, ice production as opposed to advection gain and loss.
- 5- New Objective: Develop a seasonal forecast model for sea ice extent using satellite-derived ice concentrations, PIOMAS ice thickness, RGPS ice deformation, Reanalysis atmospheric data

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and Lagrangian sea-ice back trajectories to estimate thermodynamic and dynamic (advection) ice loss.

APPROACH

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We plan to use satellite-derived and climate model simulated sea-ice drift to produce backward trajectories of sea ice from the marginal ice zone and all peripheral seas. For the goals cited above, the back trajectories will be initiated just before the melt season and extend to the beginning of the floe's life when it was first formed. Analysis of source regions for sea ice melting in the peripheral seas and within the marginal ice zone is performed from both observed and modeled datasets. In the case of satellite-derived observed drift, sea ice age will also be calculated at each position of the back trajectories. For the simulated drift, we will calculate the sea-ice thickness (mean and amount from each different ice thickness category available) as well as sea ice age.

The work will require development of code to interpolate the observed velocity field on the exact latitude/longitude location of the Lagrangian trajectories. In the case of model data, we will interpolate the sea ice concentration, thickness, age and velocity onto the same EASE grid on which the satellite derived data is calculated. Once this is done, the same interpolation and advection routines will be used as for the observed data.

WORK COMPLETED

All datasets, including passive microwave derived sea-ice concentrations, ice thickness from the PIOMAS model, ocean bathymetry, and satellite derived sea-ice drift were interpolated on the 25 km EASE grid. We developed simple and relatively efficient Matlab routines to interpolate any field onto the EASE grid using latitude, longitude and field itself as input. The dataset and routine will soon be made publicly available at portals based on LamontDoherty Earth Observatory and McGill University servers. We will continue to build on these data and plan to include PIOMAS ocean currents, RGPS sea ice deformation, Reanalysis surface wind, surface radiative fluxes, etc. Processing the large datasets involved is a tedious task, but the outcome of providing all observed and simulated fields of relevance for Arctic climate studies on the same grid will be very useful.

We co-organized, with researchers and practitioners with social science and policy backgrounds, a workshop entitled "*White Arctic, Blue Arctic: Exploring Sea Ice Restoration*" held at Columbia University on April 24-25. Participants in the workshop included climate scientists, politicians, geo-engineers, economists and social scientists. The goals of the workshop were to: 1- define the level of atmospheric CO₂ concentration necessary to maintain sea ice in the Arctic Ocean as per the

simulations from the Climate Models participating in the Coupled Model Intercomparison Project Phase 5 (CMIP5); 2- define the time scales for action associated with social, economic and the political systems, and those associated with the climate system; and 3- discuss ways to reduce atmospheric CO₂ level including carbon sequestration. In collaboration with the NSF-funded Climate Change Education Partnership: Polar Learning and Responding (PoLAR), and the government of Quebec, we are planning a follow-up meeting in 2014 that will address potential sea ice evolution over the coming century.

We have added features to the Ice Tracker program originally developed by Chuck Fowler at University of Colorado. The Ice Tracker is an online program that allows a user to plot the trajectory of a sea ice floe (backward or forward in time) starting from any ice covered area in the Arctic Ocean within the satellite era (1979-2013). The new Ice Tracker allows the user to select multiple trajectories, and to overlay other fields (air temperature, ice age, ice thickness, etc) on the Lagrangian trajectories. The new Ice Tracker will be hosted at Columbia University. We have organized collaboration between the Lamont-Doherty (physical systems support), the Columbia Center for New Media Teaching and Learning (web development and hosting) and our project team members to upgrade and migrate the Ice Tracker to the website of the Polar Learning and Responding Climate Change Educational Partnership (PoLAR-CCEP): <http://thepolarhub.org/>. PoLAR-CCEP was developed under a separate initiative funded by the National Science Foundation (PI: Pfirman), with objectives that are synergistic with some of ours. At its new site, users will be able to save Ice Tracker data for offline analysis and presentations. This tool is useful for a wide variety of applications including sediment, nutrient and pollutant transport by sea ice, seasonal forecasts, rescue. PoLAR-CCEP is interested in its potential as an educational tool in both formal and informal settings.

RESULTS

Lagrangian ice trajectories: We are now in a position to calculate back trajectories of the minimum sea ice edge position to its early June location. Using this approach, we can separate the total ice loss for each melt season into a thermodynamic ice loss (melt) and a dynamic ice loss (advection of sea ice out of the Arctic through Fram Strait). Idealized model experiments (Chevallier et al. in prep.) suggest that the thermodynamic ice loss is correlated with the sea ice thickness in specific ice thickness categories. Our goal is to establish the predictability of thermodynamic and dynamic ice loss using a combination of satellite-derived observations (sea-ice drift, deformation and concentration) and model-derived information such as reanalysis atmospheric fields (NCEP, ERA) or ocean-ice fields (PIOMAS). Patricia DeRepentigny, Masters student at McGill (supported by other funding sources), will contribute to this effort.

White Arctic, Blue Arctic workshop: The ensemble mean minimum sea-ice extent responds without significant lag to changes in the atmospheric CO₂ concentration. For instance, the sea-ice extent in response to RCP2.5 starts a recovery in 2040 when the CO₂ concentration starts to drop; the sea ice extent in the RCP4.5 stabilizes around 2080 when the CO₂ stabilizes; and the SIE in RCP6.0 does not reach equilibrium by 2100. The individual ensemble members exhibit interannual and decade-scale internal (unforced) variability, but on a longer time scale their behavior also reflects changes in the forcing. Thus, rapid ice response to forcing is a robust feature of both the ensemble means and the individual members. This is in contrast with the popular notion of a tipping point often cited to describe the Arctic sea ice system, which raises concerns that once sea ice is lost, it will not recover. The CMIP5 models clearly suggest that a change in greenhouse gas forcing results in responses in the sea ice areal extent on climate time scales.

According to political scientists and environmental law experts attending the WABA workshop, the political time scale to implement changes in policies that would affect CO₂ emissions and ultimately the state of Arctic sea ice is around 25 years. The technological time scale associated with the development of geo-engineering tools to reduce atmospheric CO₂ levels is also, participants agreed, on the order of a few decades. A fascinating novel result of the interaction of the various distinct fields in the workshop was a discussion of the results of an eventual mitigation of CO₂ concentrations in the atmosphere. One fairly likely implication for the Arctic is that the summer sea ice will disappear over the coming several decades, followed by rapid development of industrial, commercial and transportation infrastructure. If CO₂ concentrations are ultimately corrected back to 20th Century ranges, the sea ice is likely to return quickly to the summer Arctic climate, resulting in a new and novel set of conflicts over reversing economic development there. Thus the workshop found that it would be possible to halt the decline in sea ice extent, and even to restore Arctic sea ice within this century, if there were the international will to do so. The workshop also defined a set of follow up research questions.

IMPACT/APPLICATIONS

The validation of climate models against Lagrangian back trajectories will provide a new lens to assess global climate models strengths and biases. In particular, comparing the source regions for sea ice populating the marginal ice zone and peripheral seas during the summer melt season from observations and GCMs will help reduce uncertainties in projections of future sea ice extent. The Lagrangian back trajectories derived from satellite derived sea ice drift can also be used for seasonal forecasting purposes. Spinoffs from this project include the Ice Tracker tool that has a wide range of applications including from educational, scientific and environmental issues.

The availability of Lagrangian ice tracking will also provide an important input to studies of the dynamics of the Arctic Ocean circulation and the distribution of seawater properties in the Arctic.

RELATED PROJECTS

The role of ocean heat fluxes in the Arctic sea ice mass balance.

The CCSM3 and CCSM4 have drastically different projections of minimum sea ice extent in the 21st century simulations. The CCSM3 simulations show rapid sea ice declines that occur as early as 2040, after which the Arctic is virtually ice free. In CCSM3 all rapid sea ice declines are preceded by a pulse of Atlantic water heat into the Arctic that leads to more open-water formation, shortwave radiation absorbed in the surface ocean and in turn even more open water formation. The CCSM4 on the other hand shows a nearly linear decline with ice-free conditions near the end of the 21st century.

Preliminary results show that in CCSM3, Atlantic Ocean heat enters the Arctic mainly via the Barents Sea branch while in the CCSM4 most of the Atlantic heat enters the Arctic via the West Spitsbergen current. In the former case, Atlantic heat is in direct contact with sea ice before diving to the depth level at which it achieves dynamic equilibrium; in the latter case, the Atlantic heat enters the Fram Strait at depth and little heat is vertically mixed leading to sea ice loss. The different behavior between these two models and the different preferred path for Atlantic heat to enter the Arctic suggests that the partitioning of heat between the Barents Sea and West Spitsbergen branch and local atmospheric forcing plays a crucial role in future sea ice decline.

Using a high resolution (4 km) ice-ocean model forced with contemporaneous wind forcing shows large vertical ocean heat fluxes, in line with observations by McPhee et al. (2005), at the edges of sea-ice floes moving differentially at active sea-ice leads. Discontinuities in the surface ice-ocean stresses and resulting Ekman divergence drive intense vertical motion beneath these leads. The magnitude of the ocean heat flux and vertical velocity vary linearly with the magnitude of the curl of the ice-ocean surface stress. The anomalous vertical velocities and ocean heat fluxes extend hundreds of meters below the surface, well below the Cold Halocline Layer and into the Atlantic Layer. These events are localized in space and time, but can bring large amounts of heat to the surface mixed-layer. In a future climate with thinner ice, projections indicate more mobile pack ice, which would only amplify these fluxes. We are in the process of quantifying the large scale integrated effect of Ekman driven ocean heat flux on the Arctic sea ice mass balance.

World Wildlife Fund, 30K, *Sea ice extent across the Canadian Arctic, 09/2012 – 12/2012.*

Global climate models participating in CMIP5 are being evaluated for the timing of melt onset, freeze-up, end of winter snow depth and ice thickness within the Canadian Arctic Archipelago (CAA). We produced spatial distributions of the above quantities from all CMIP5 climate models for today's climate, mid 21st century and end of the 21st century. The analysis was repeated with a high resolution (4 km) coupled ice-ocean model of the pan-Arctic (MITgcm) forced with atmospheric fields an atmospheric field from the global version of the MITgcm for the same time intervals. Results show that the sea ice retreat within the CAA is not significantly different when using a lower resolution CGM (the GFDL model) that does not resolve all the narrow passages of the CAA, versus a high-resolution ice-ocean model forced by the atmospheric field from the same GCM. This implies that thermodynamic melt of perennial sea ice within the CAA may be more important than dynamic transport of multi-year ice, at least in the more southern regions where ice can melt. The goal was to characterize the likely geographical pattern of sea ice retreat within the CAA during the next century. These analyses will serve as input for planning activities of WWF efforts to prevent habitat loss for sea-ice dependent species.

Environment Canada, Grant and Contribution, 35K/year, *Sea ice dynamics within the Canadian Arctic Archipelago, 06/2011 – 05/2014.*

A dynamical sea ice model was developed that includes tensile strength. The presence of landfast sea ice in the Arctic and sea ice arches in narrow passages of the Canadian Arctic Archipelago are clear indications of the presence of the tensile strength of sea ice at finer spatial scales. We are now developing a linear elastic solid model to determine the area covered by landfast sea ice. The edge of the landfast sea ice will then be used as the "new" solid boundary for our viscous plastic sea ice model. The completion of this work will yield a model that is applicable to both the Arctic proper and the narrow passages of the Canadian Archipelago.

We have completed the analysis of the ice stress buoy deployed in the Canadian Arctic Archipelago (CAA) in October 2010. Internal sea ice stress measurements when the sea ice is landfast clearly show that landfast sea ice in the CAA is anisotropic. The anisotropy comes from the c-axis alignment of the ice crystals in the direction of the ocean currents in coastal areas (Weeks and Gow, 1978). Anisotropy in sea ice leads to internal sea ice thermal stresses that vary with orientation and can impact the orientation of fracture line and deformation in coastal areas. This has direct implications for the simulation and forecast of the landfast ice edge in the CAA (and along the Alaskan coastline where

anisotropy is also observed). Consequently it is important to the security of local populations that use landfast ice as a platform for hunting and fishing.

Indian and Northern Affairs, Beaufort Region Environmental Assessment, *The development of efficient sea ice implicit solver for viscous-plastic sea ice model, 35K/year, 06/2011 – 05/2015*.

New preconditioners are being developed for the GMRES component of our Jaobian Free Newton Krylov solver for the momentum equation of sea ice. The goal is to improve the convergence of numerical solvers particularly at high resolution when failure to converge is often present.

The failure to converge is often linked with grid points at boundaries. In parallel, we are revisiting the boundary conditions (no slip) used to solve the momentum equations for viscous plastic sea ice models. In particular we are developing boundary conditions defined on the stresses rather than on the ice velocities at the boundary, following the practice in the field of mechanics of material.

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PUBLICATIONS

Bouchat, A. and Tremblay, L.B., “Energy Dissipation in Viscous-Plastic Sea-Ice Models”, *Journal of Geophysical Research*, [submitted, peer-reviewed].

Sirven, J. and Tremblay, B. “Analytical study of an isotropic visco-plastic sea-ice model in idealized configurations”, *Journal of Physical Oceanography*, [accepted for publication, peer-reviewed].

HONORS/AWARDS/PRIZES

Tremblay, Bruno, McGill University: Landolt Chair “Innovations for a Sustainable Future”, École Polytechnique Fédérale de Lausanne and Landolt Bank, Switzerland, [declined].